Geant4 liquid Argon Validation

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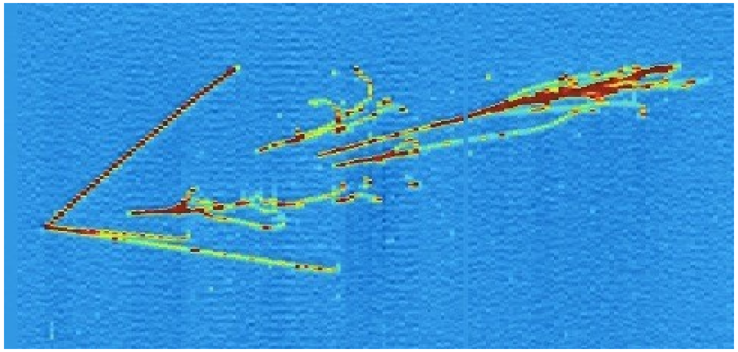
Outline

- Validation of LAr TPC physics
  - Hadronic Cross Sections
  - Electromagnetic showers
  - Muon separation



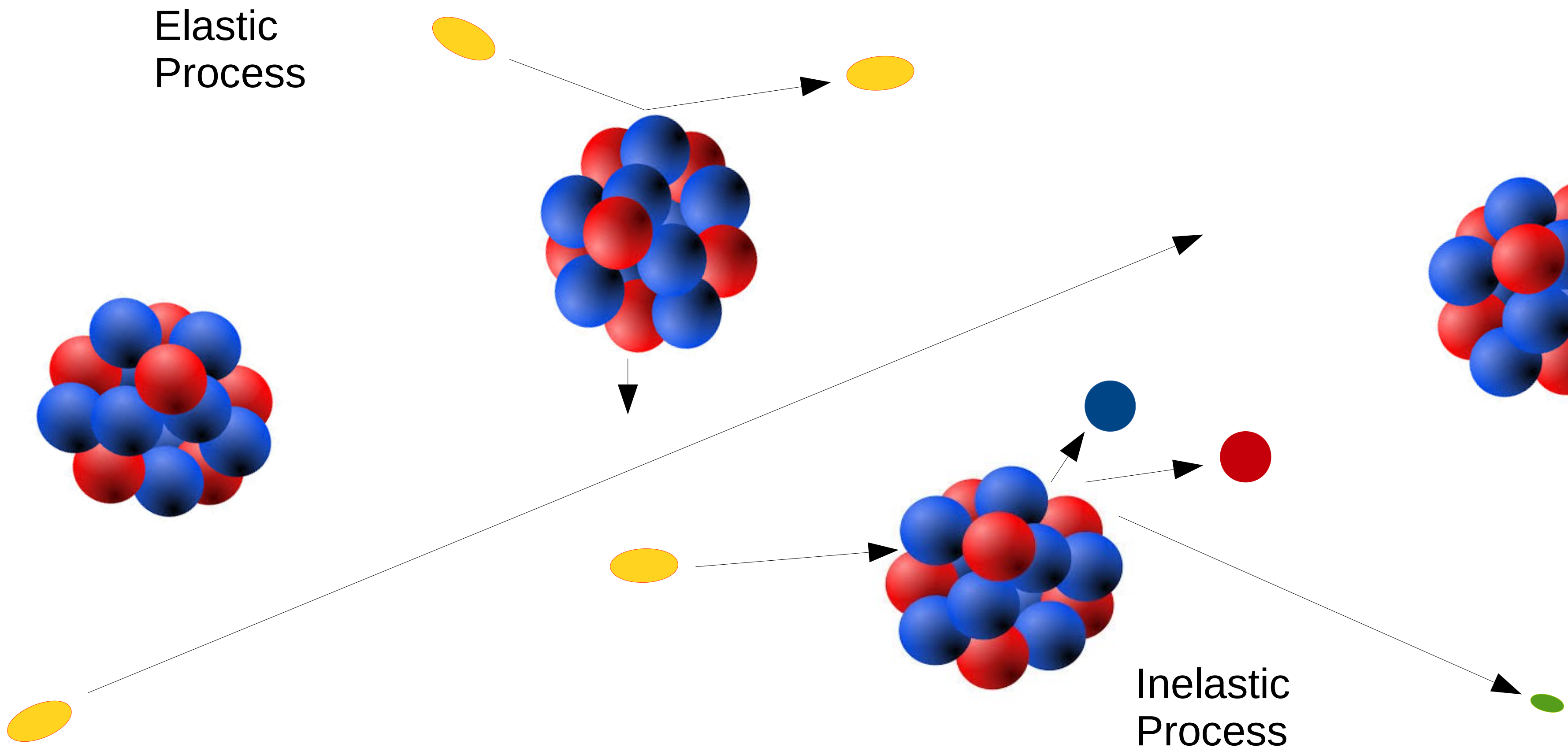
- Simulation of Liquid Argon TPC
  - Introduction
  - Step Limiter
  - Divided Steps
  - Segmented Geometry

Introduction

The scope of this project was to look into various physics processes relevant to Liquid Argon TPC detector response.

In addition, we were interested in the details of LArSoft simulation and to explore alternative methods to implement the simulation.

Hadronic XS



$$XS = \frac{N_{interacted}}{N_{total}} \cdot \frac{A}{N_a \cdot d \cdot T}$$

Hadronic XS

- Pions, Kaons, Nucleons

- Cross Sections in Liquid Argon, no experimental data

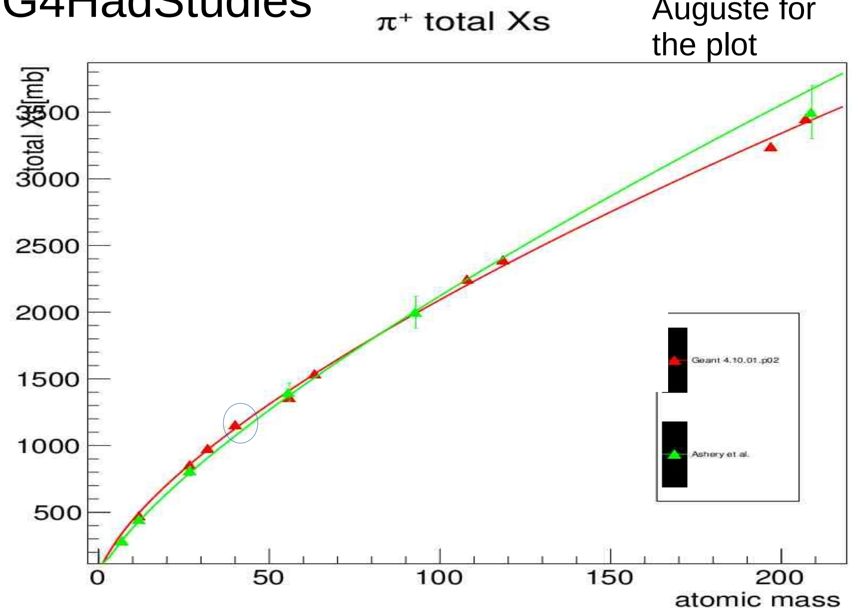
- Comparison with experimental data in Carbon and other materials

- Geant4: → https://github.com/hanswenzel/G4HadStudies

- Start Event. Use Sensitive Detector (Stepping Action) to detect interactions:
  Elastic interaction might not put new particle on the Stack (UserStackingAction)
- If Inelastic or elastic interaction, increment
- Calculate XS from number that interacted

We know what to expect:
The cross section scales linearly with A^(2/3)

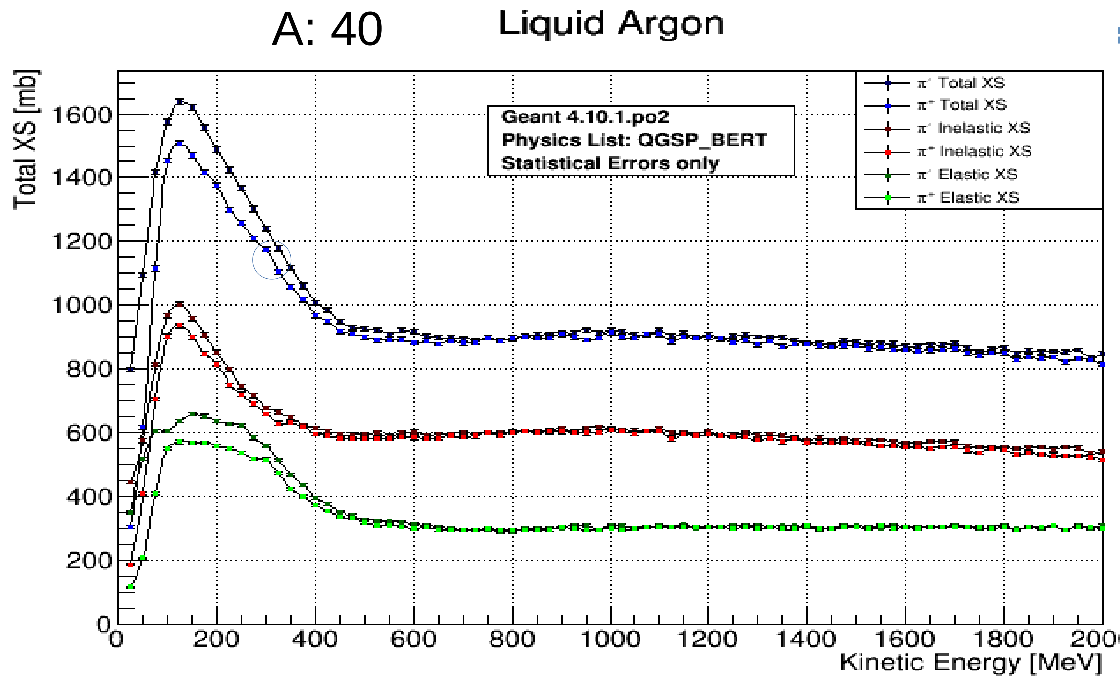
Thanks to Rasheed Auguste for the plot



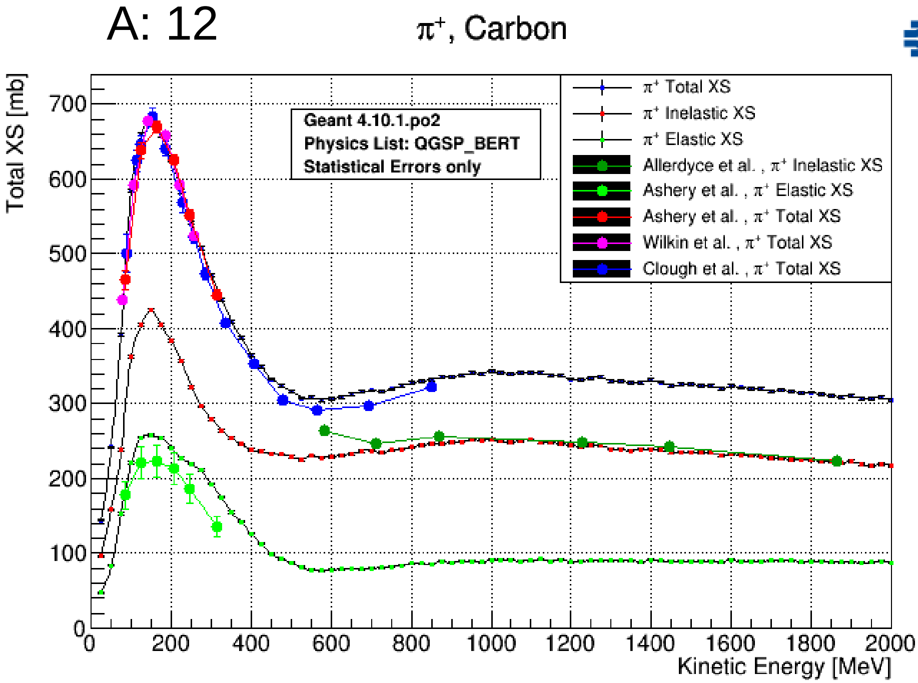
Pion Cross Section

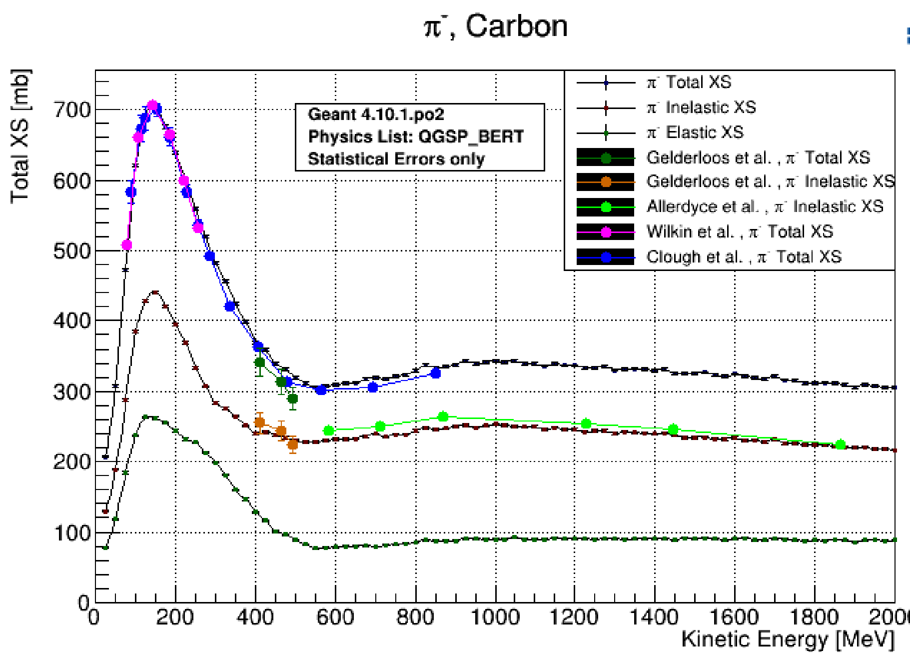
- Matches well with experimental data

A: 40



A: 12

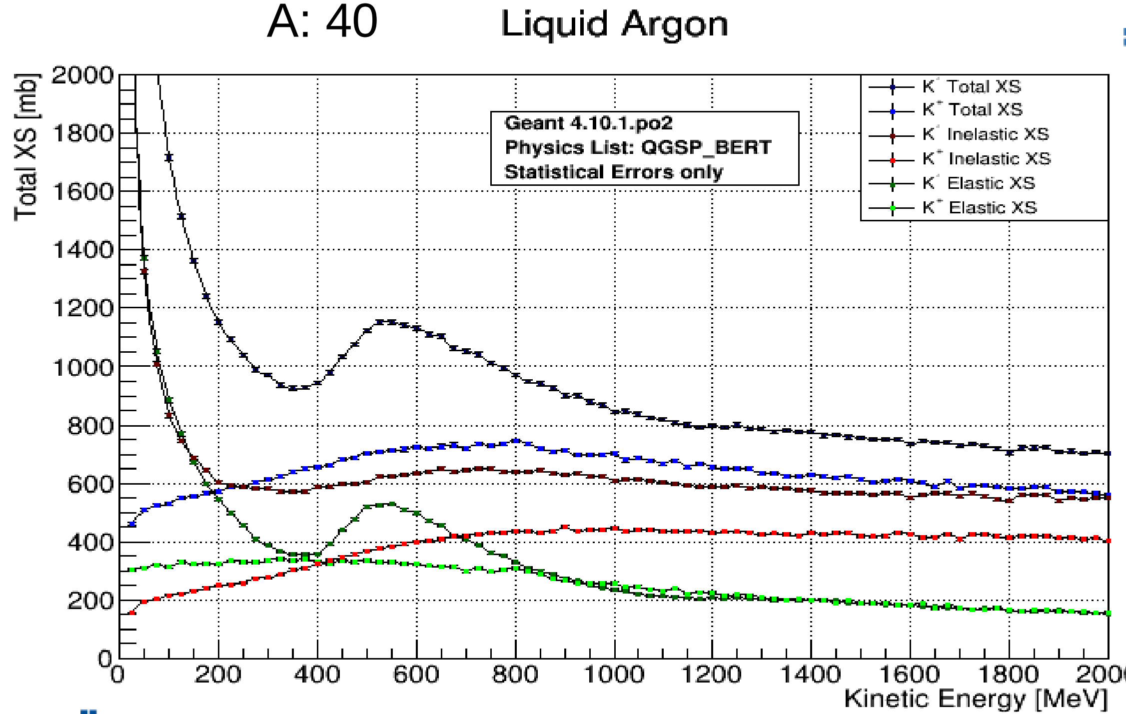




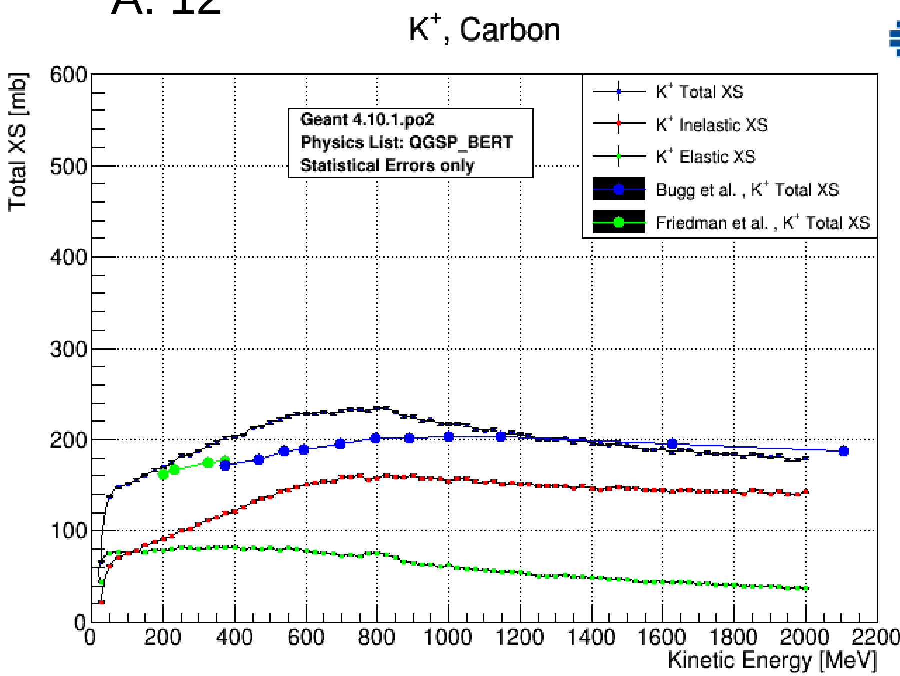
Kaon Cross Section

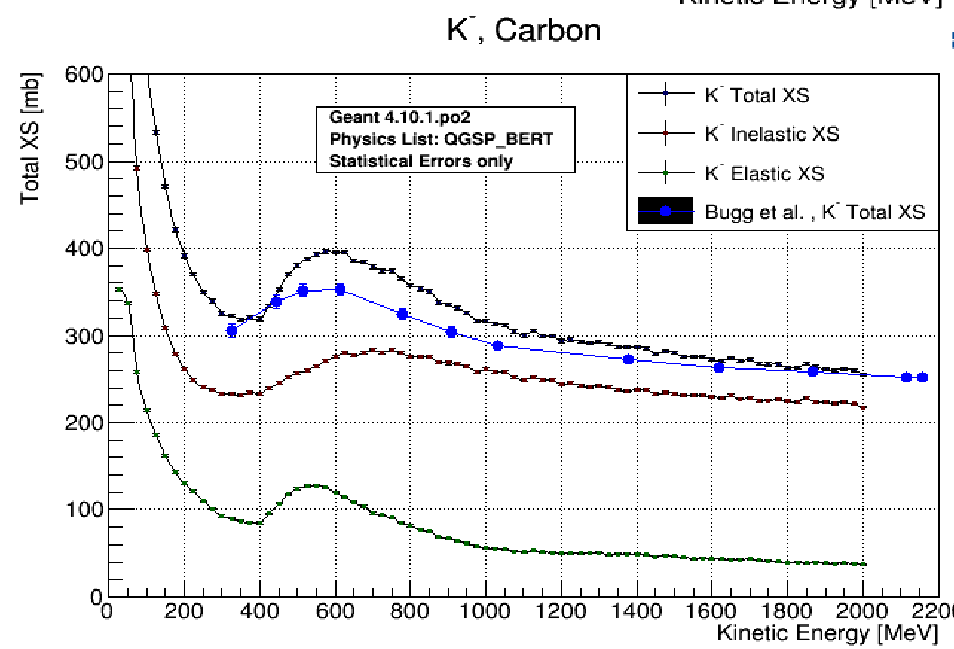
- Matches poorly with experimental data

A: 40



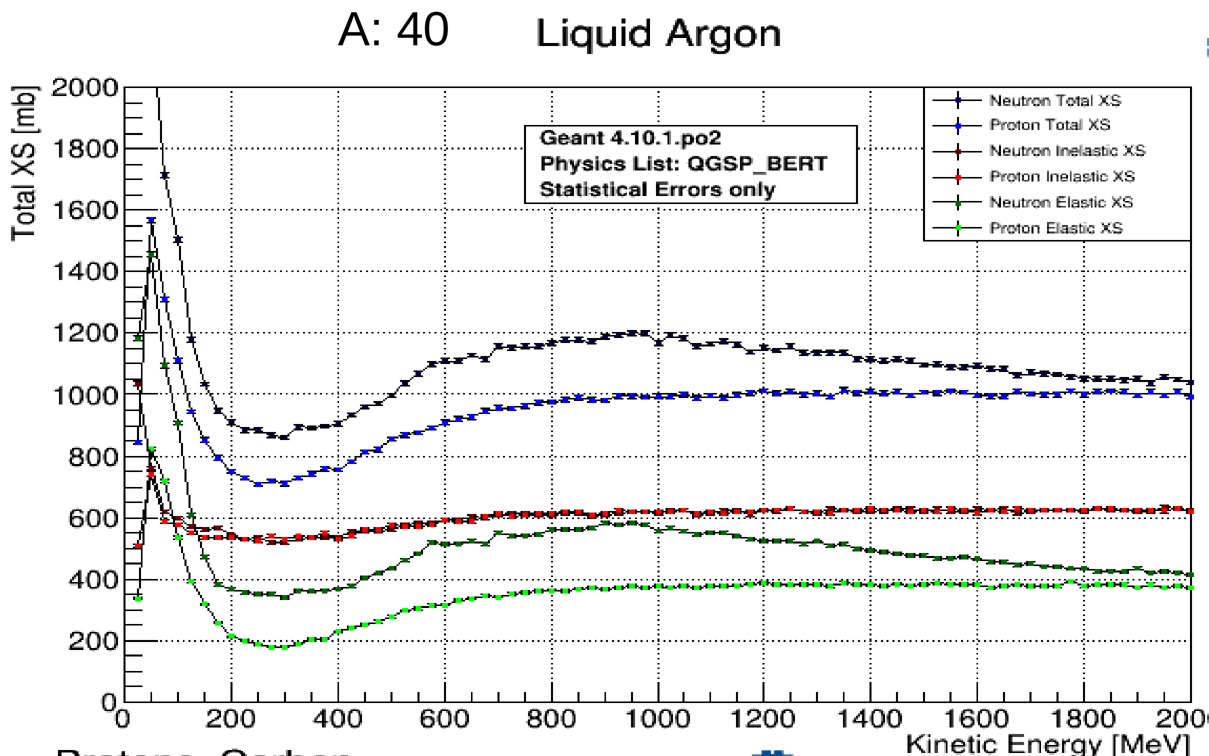
A: 12

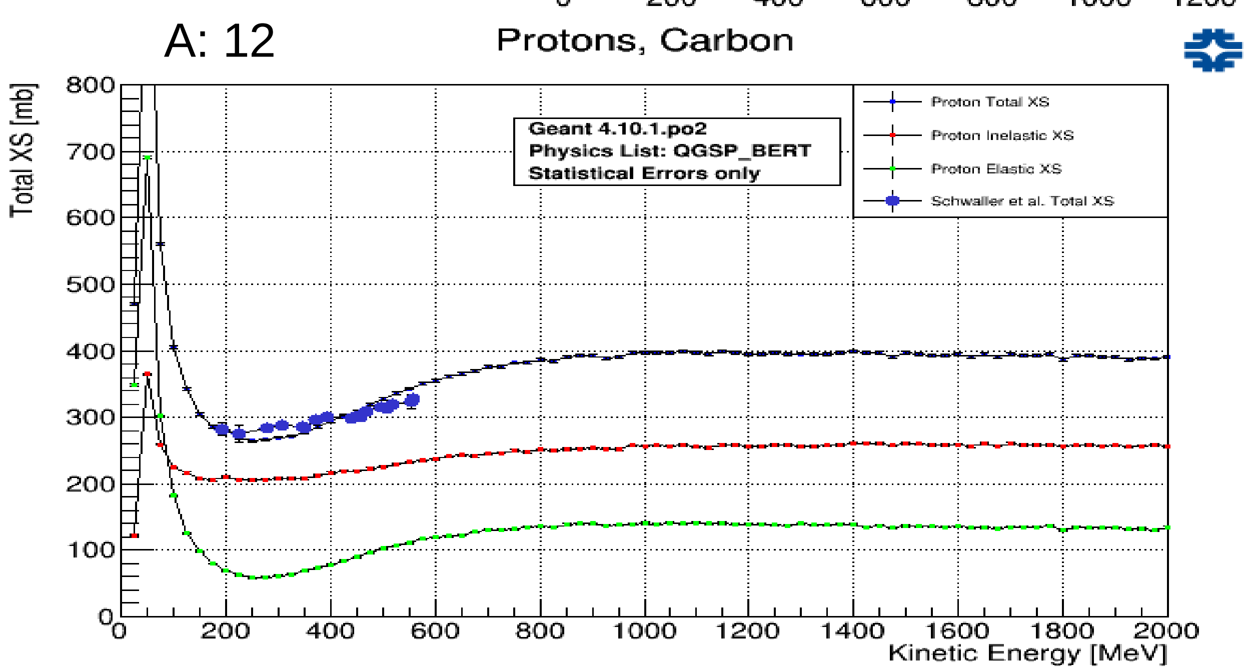




Nucleon Cross Section

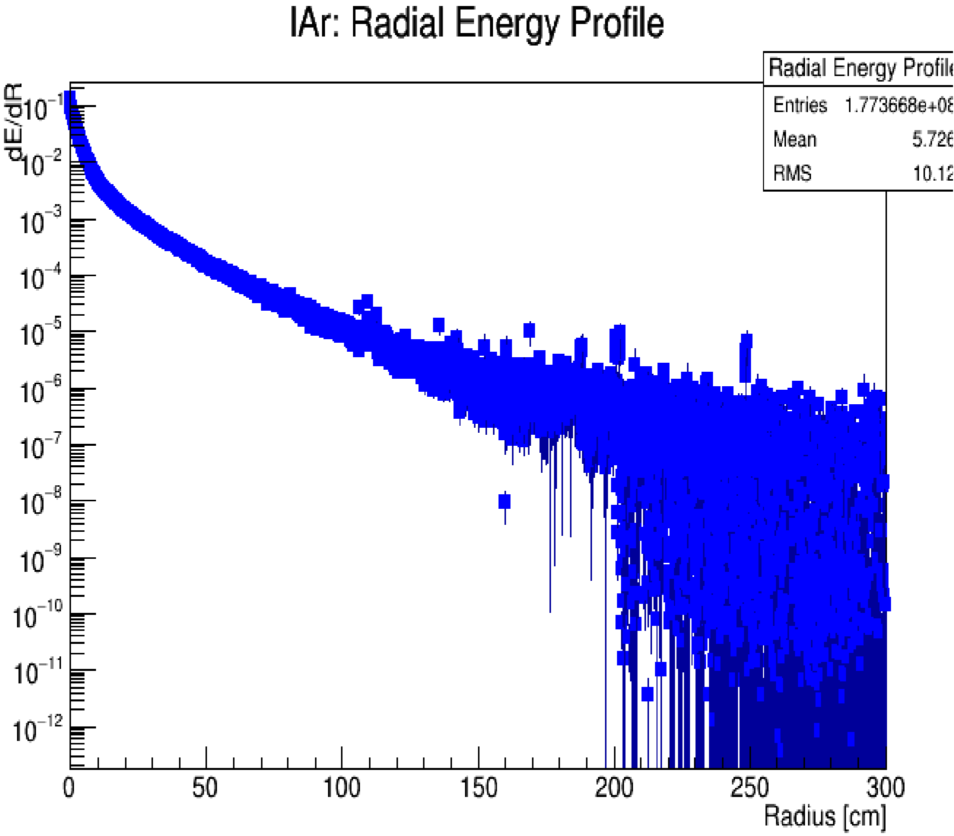
- Matches well with experimental data

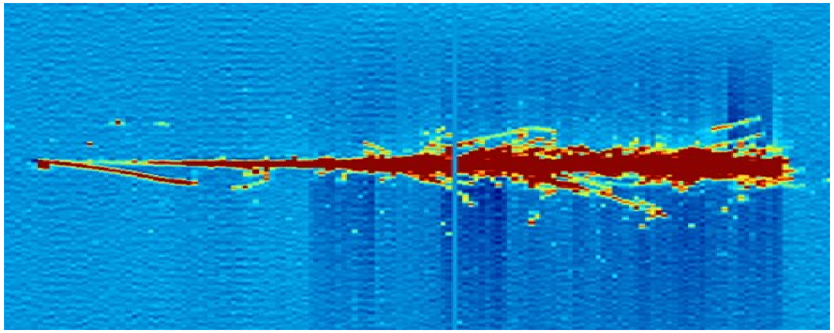




Transverse Shower Profile

- Sensitive Detector: Stepping Action
- Collect energy deposited from shower run
- Integrate histogram until at 90% of total integral
- Molière Radius always comes out high compared to literature values
- This has been brought up before
- $dE/dX = a\mathbf{e}^{-r/R_m} + b\mathbf{e}^{-r/\lambda_{min}}$





	Simulated	Literature [cm]
Pb:	**1.95**	**1.6**
Fe:	**2.79**	**1.72**
lAr:	**14.34**	**10.1**

Muon +/- Separation (50MeV)

Processes	μ-	μ+
Decay*	**e-**, $\bar{\nu}_e$, ν_μ	**e+**, ν_e, $\bar{\nu}_\mu$
Lifetime	.58μs	2.2μs
Probability	25%	100%
Capture	ν_μ, **γ** **	none
Probability	75%	

* for **μ-**, it is Decay in Orbit

there can be more than one **γ emitted in nuclear capture

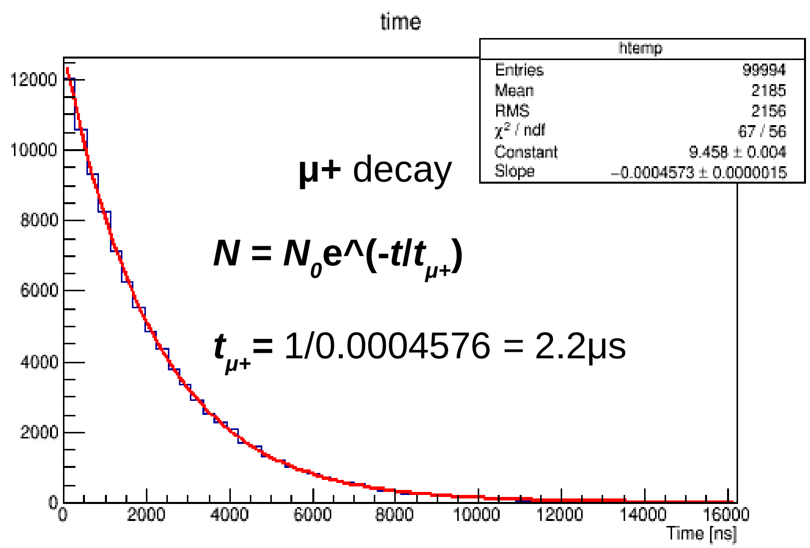
Stacking Action: look at particles, processes, energies, and timing when new particles are put on the stack

Muon Decay

[MeV]

- $\mu+ \dashrightarrow$ e+, ν_e , $\bar{\nu}_\mu$

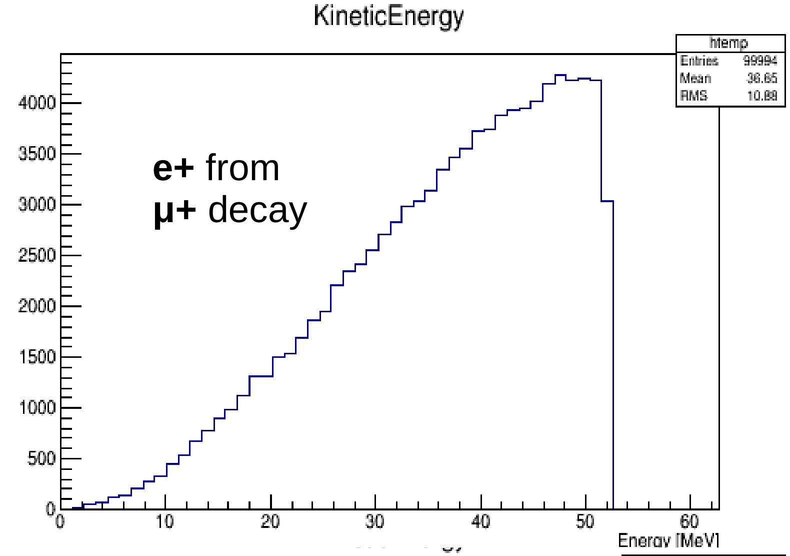
- $\mu- \dashrightarrow$ e-, $\bar{\nu}_e$, ν_μ, X



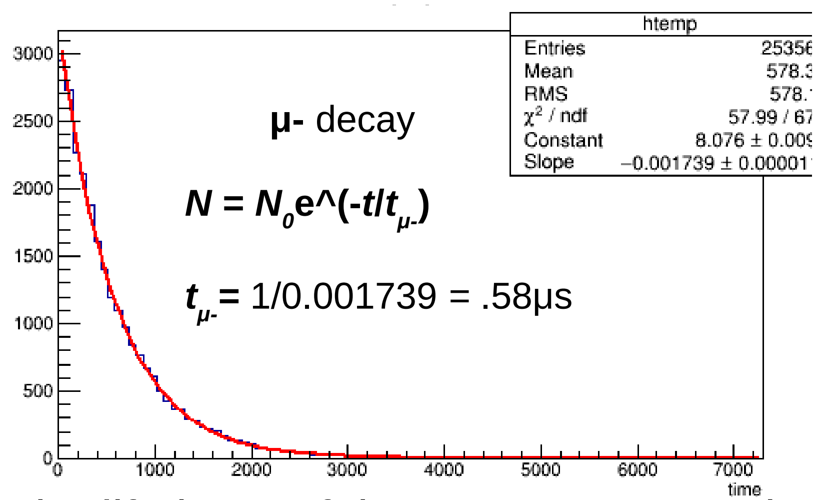
μ+ decay

$N = N_0 e\text{^}(-t/t_{\mu+})$

$t_{\mu+}$= 1/0.0004576 = 2.2μs



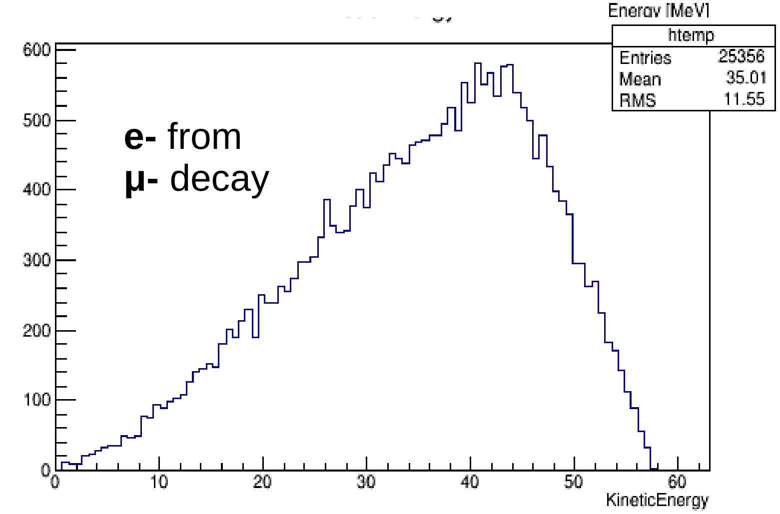
e+ from
μ+ decay



μ- decay

$N = N_0 e\text{^}(-t/t_{\mu-})$

$t_{\mu-}$= 1/0.001739 = .58μs

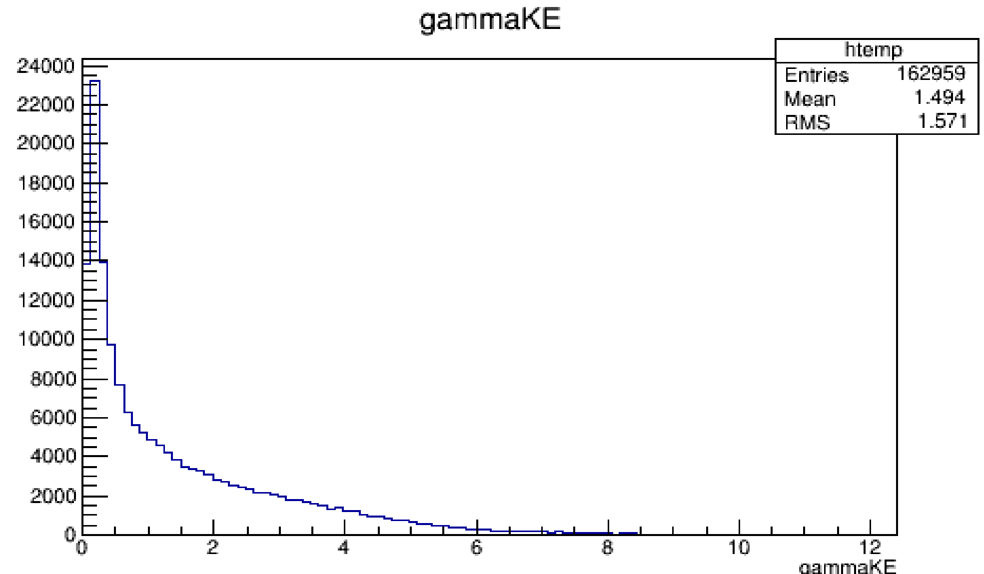


e- from
μ- decay

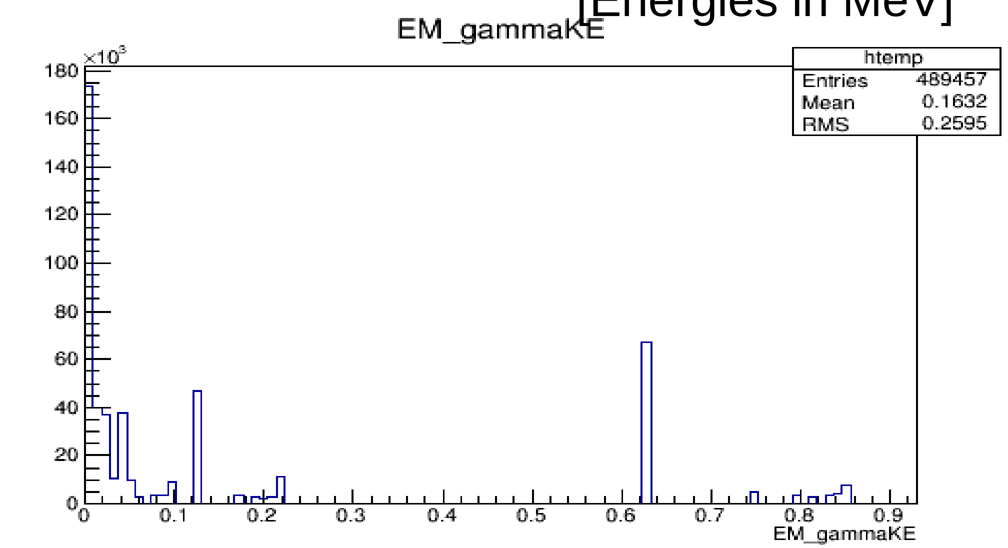
The values for the lifetimes of the muons are consistent with findings from previous experiments. Suzuki et al measured mu- lifetime in liquid Argon, and it is ~.58 μs

Muon Nuclear Capture

- **μ- only**
  $\boldsymbol{\mu^- + p \rightarrow n + \nu_\mu + \gamma}$
- Radiative, gammas produced
- Low energy gammas from atomic capture produces spectrum



[Energies in MeV]



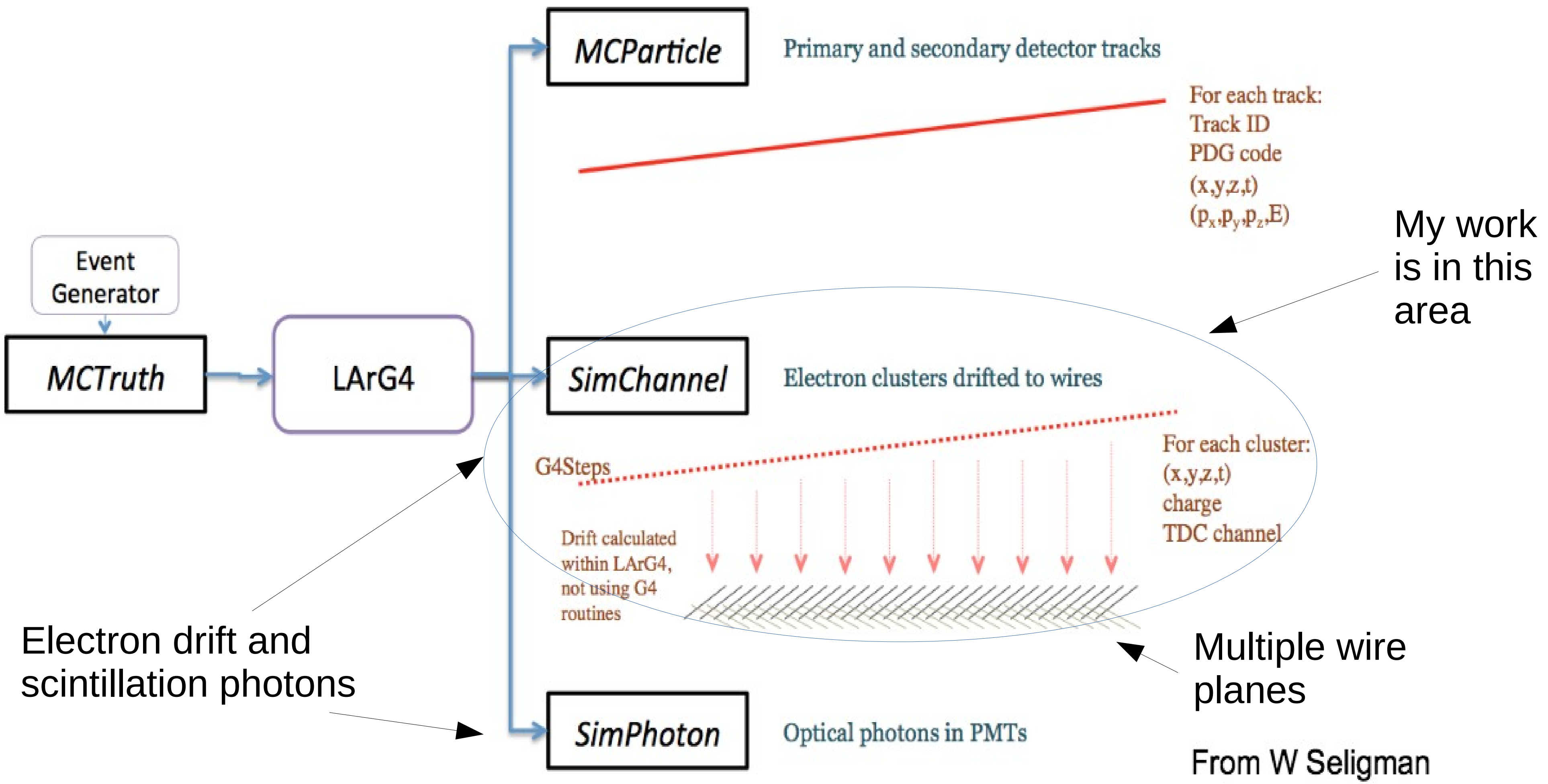
Part II:
LAr TPC Simulation

Liquid Argon Specifics

- Steps must be matched to readout pitch
- Scintillation and Ionization compete
- dE/dX = 2.1 MeV/cm
- Ionizing: 23.6 eV per electron pair
- Scintillation: 19.5 eV

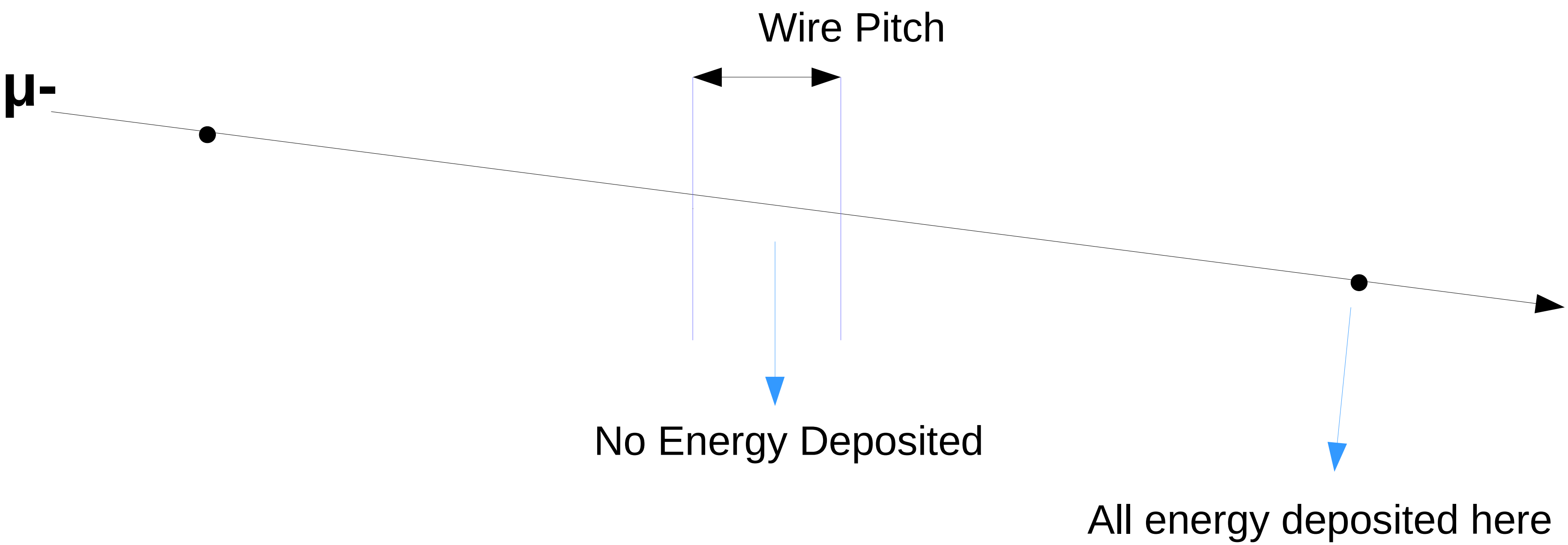
$\Big\}$ (Ereditato)

Detector simulation



From W Seligman

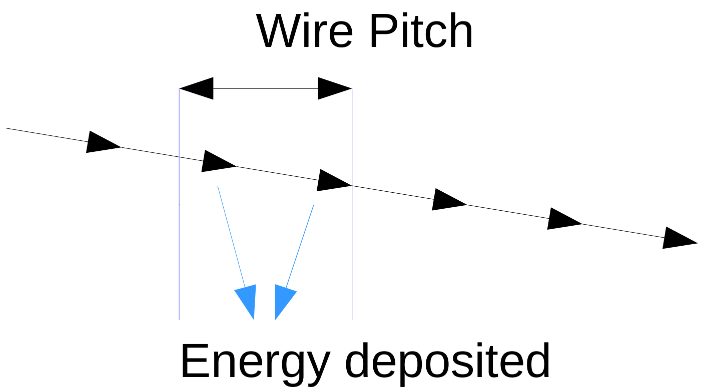
Matching Step Length and Readout Pitch



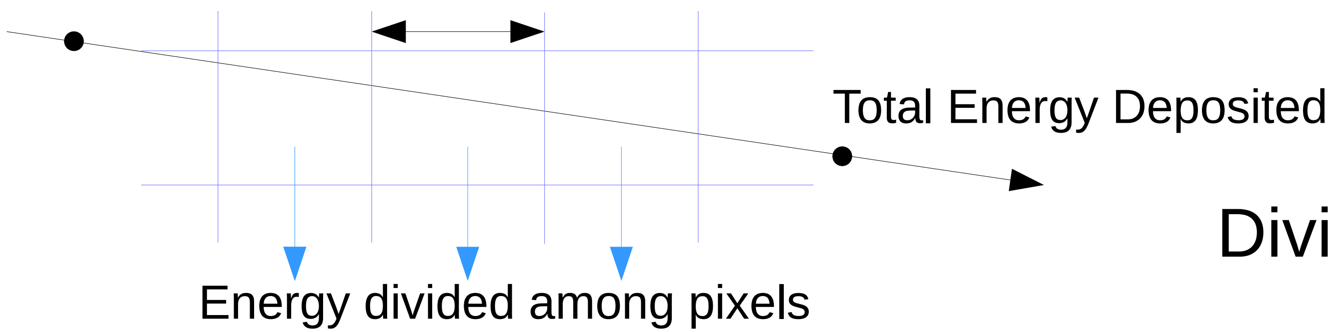
Geant4 adjusts the step size according to the physics, and for some processes, the step size is much greater than the readout pitch.

For energy deposits, we expect landau distributions with a most probable value at 2.1 MeV/cm (muon approximates minimum ionizing particle)

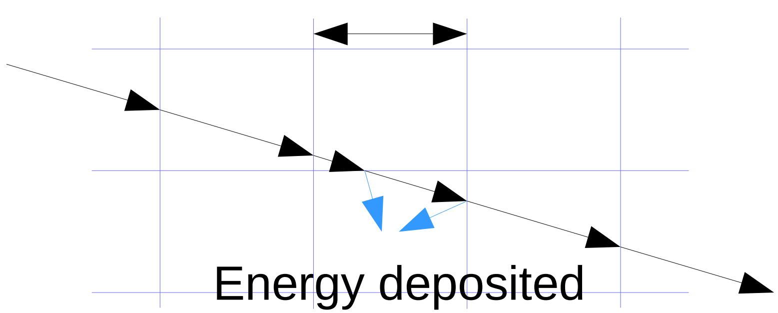
Solutions



Step Limiter



Divided Step



Segmented Geometry

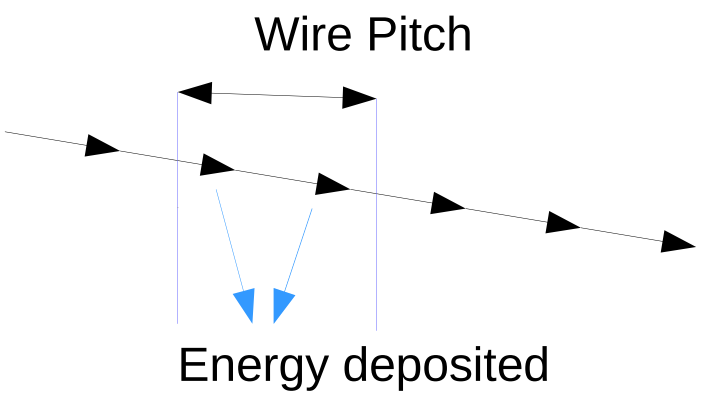
Step Limiter

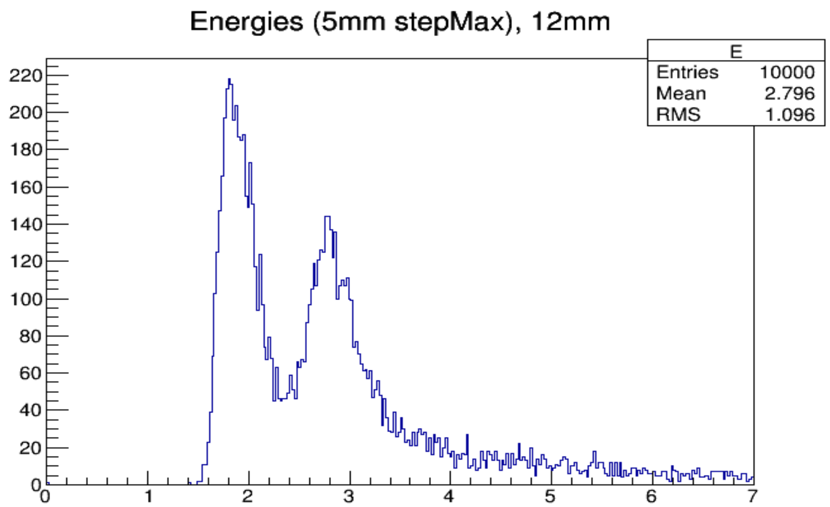
+ Very Simple to implement

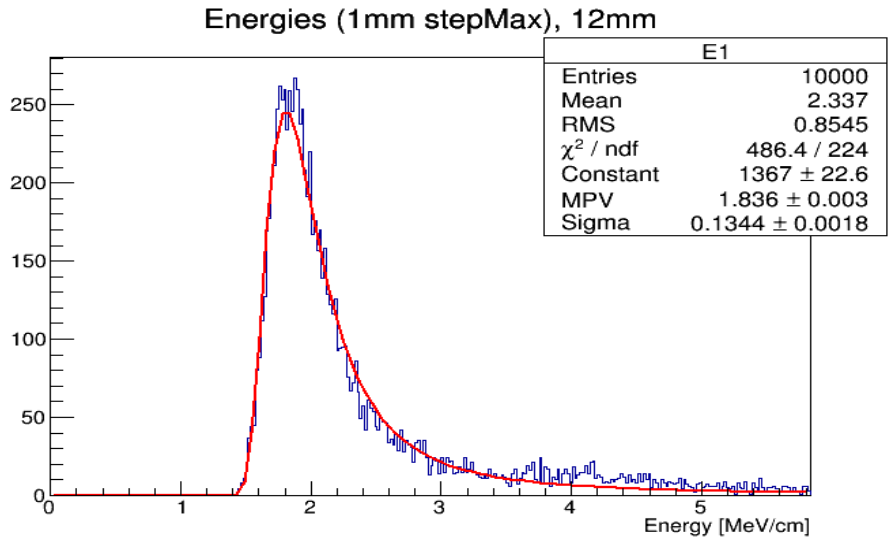
+ No added memory costs

+ Gets physics right when Step limiter is about one tenth of the wire pitch

- Takes a long time for small step sizes (> .72 sec/event, .1 mm)







Step Limiter

- In DetectorConstruction.cc:

```
G4UserLimits *fStepLimit = new G4UserLimits(maxStepSize);
DetectorLogicalVolume -> SetUserLimits(fStepLimit);
```

- In g4main.cc:

```
phys->RegisterPhysics(new G4StepLimiterPhysics());
```

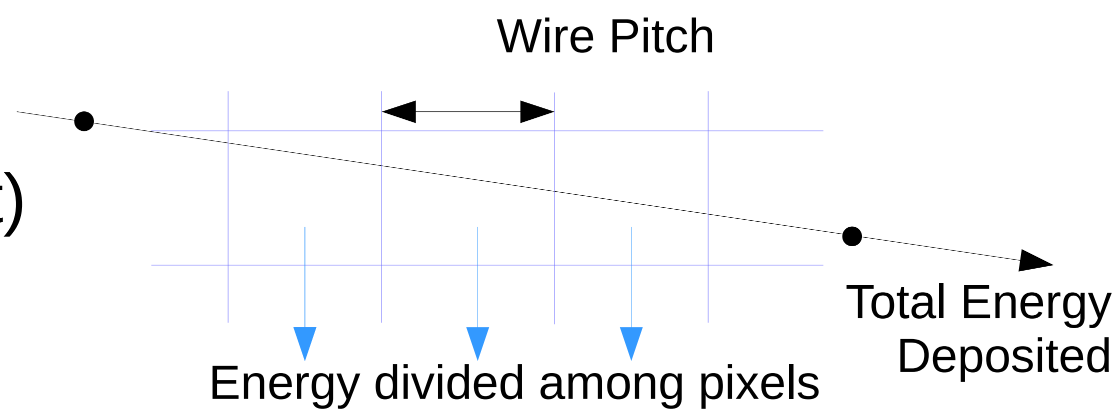
G4VModularPhysicsList

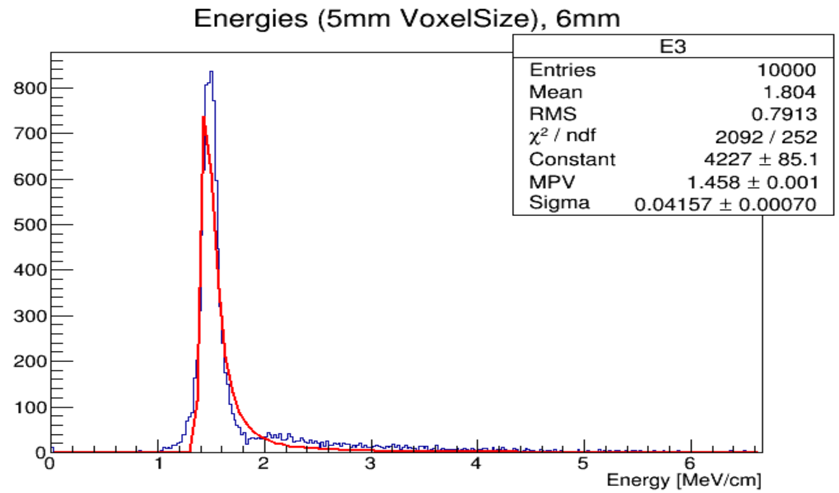
Divided Steps

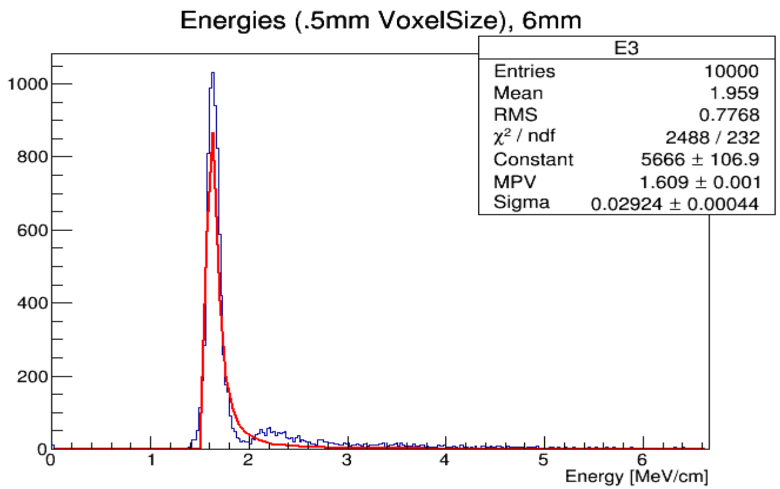
+ Takes little time even for many Divisions (< .06 sec/event)

- Huge memory costs for many pixels

- Never gets the physics right







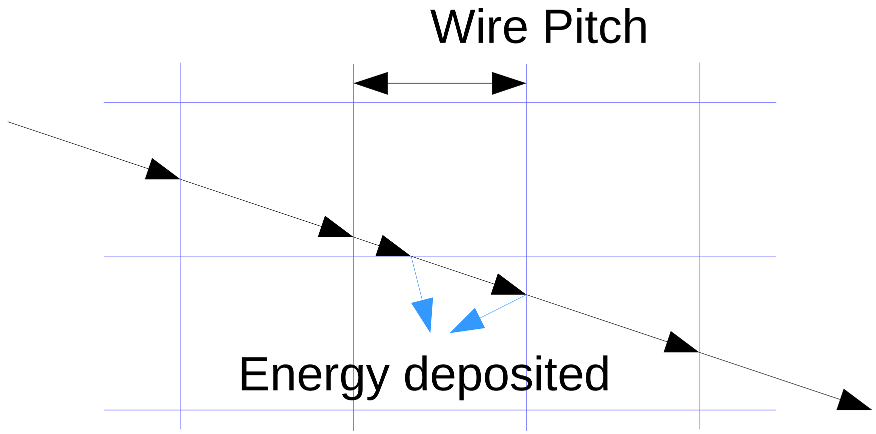
Segmented Geometry (Voxels)

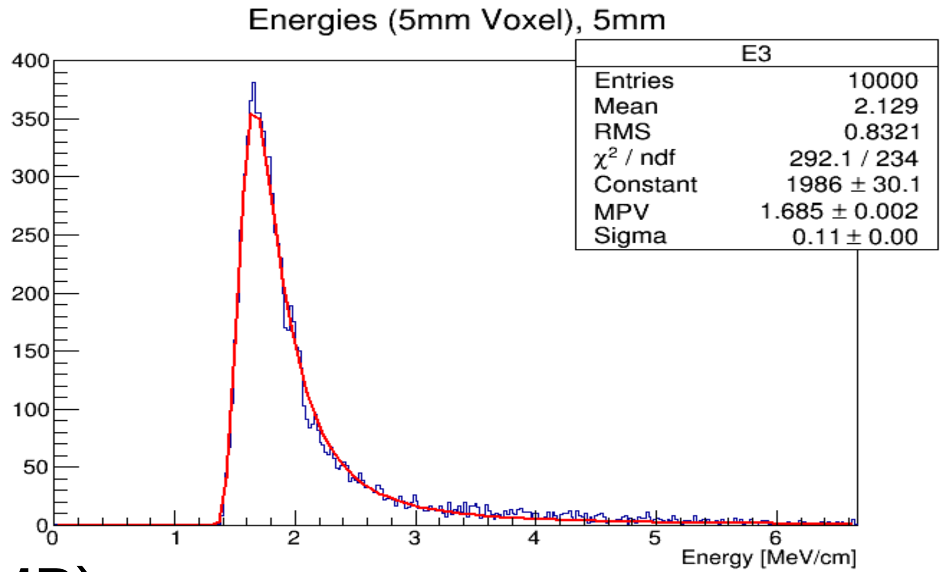
+ Gets physics right when readout matches division size, otherwise acts as step limiter

- Deals with many volumes
  Ex: 1m TPC & .3 mm cubes
  = **37,000,000,000** volumes

- Takes a long time for small voxel sizes (>.9 sec/event, .1 mm)

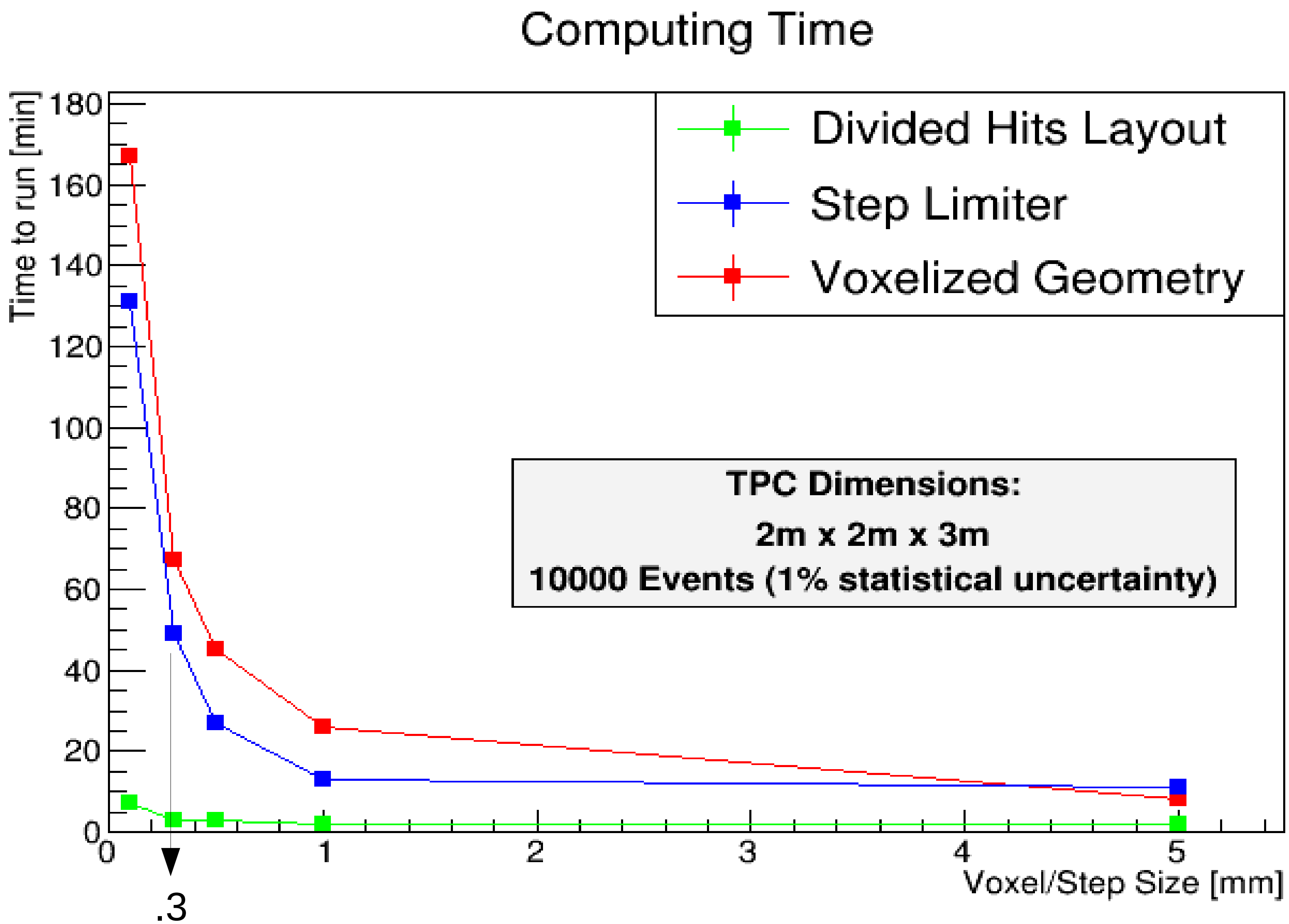
- Cannot match wires exactly to voxels (stereo readout)





- Very little added memory costs (10MB)

Timing Comparison



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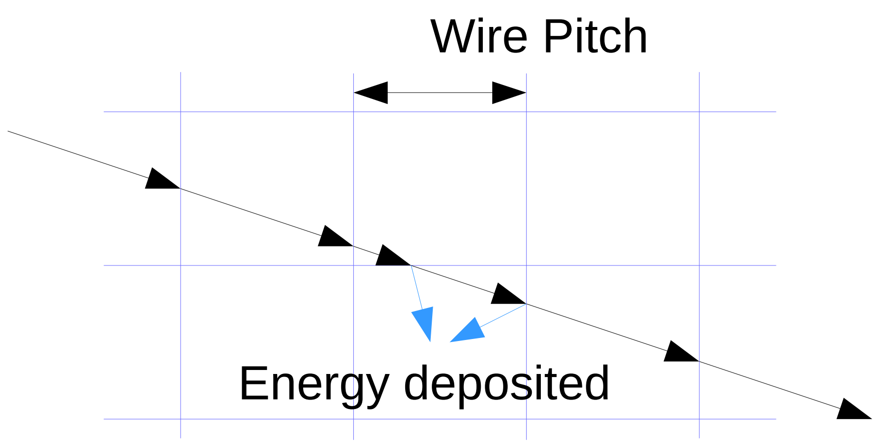
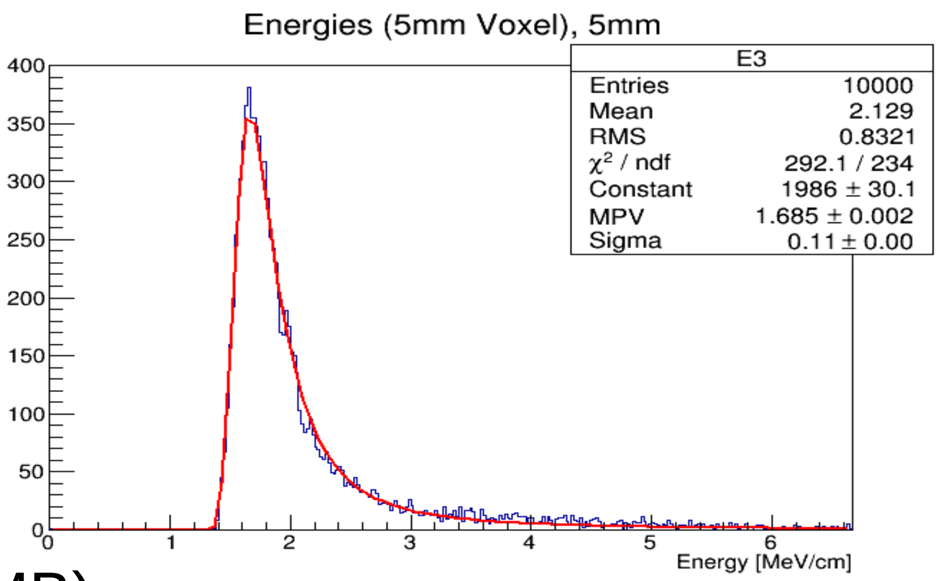


- Deals with many volumes
  Ex: 1m TPC & .3 mm cubes
  = **37,000,000,000** volumes

- Takes a long time for small voxel sizes (>2.5 hrs for 10,000 muons, .1 mm)

- Cannot match wires exactly to voxels (stereo readout)



- Very little added memory costs (10MB)

Conclusion

- In general, there was good agreement between Geant4 simulation and experimental data
- The Moliere Radius Studies aren't conclusive, studies need follow-up
- Evaluated three ways to match the step length to the wire pitch, and the step limiter is a good alternative to the segmented geometry which is currently in LarSoft/LArG4

Thank You!

- Hans Wenzel
- Metcalf Program
- Fermilab PDS group
- LArIAT